Paleoceanography and Paleoclimatology

COMMENTARY
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Key Points:

- The importance of a paper by Modestou et al. (2020) is explained, which reports middle Miocene benthic foraminifera clumped isotope data
- Ways in which a large Antarctic ice sheet can be reconciled with a warm deep ocean and moderately high CO_2 are explored
- More broadly, I argue that recent advances in proxy methodology are resulting in ever increasing confidence in paleoclimate reconstructions

Supporting Information:

- Supporting Information S1

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Deep Heat: Proxies, Miocene Ice, and an End in Sight for Paleoclimate Paradoxes?

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Abstract The mid Miocene represents an important target for paleoclimatic study because the atmospheric CO_2 concentration ranged from near modern values to ~800 ppm, while a large, dynamic Antarctic ice sheet was likely to have been present throughout much of this interval. In this special issue, Modestou et al. (2020) (doi.org/10.1029/2020PA003927) reconstruct deep ocean warmth based on the clumped isotopic composition of benthic foraminifera, a technique that allows the ice volume and thermal components of the benthic oxygen isotope stack to be separated. These data reveal a very warm deep ocean while simultaneously suggesting that continental ice volume may, at times, have been greater than today. Here, I review these results in the context of recent developments in geochemical proxies and ice sheet modeling, and explore how the presence of a large Miocene ice sheet could be reconciled with CO_2 at least as high as present. More broadly, I argue that many of the 'paradoxes' that pepper the paleoclimate literature result as much from our imperfect understanding of the proxies, as from our understanding of the climate system. Robust proxies with a well-understood mechanistic basis, as employed by Modestou et al. (2020), as well as advances in model-data comparability usher in a new era of palaeoclimate research; an exciting future of untangling Earth's myriad past climate states awaits.

Plain Language Summary Reconstructing climate variation in Earth's geologic past informs us of the broad features of warm climates, which is relevant to preparing for climate change over the coming centuries. Moreover, these data can be compared to state-of-the-art climate models, which provides a test of the degree to which our models can reproduce warm climate states. A paper recently published in this journal applies a new method in order to reconstruct the temperature of the deep ocean in the middle Miocene (between 17 and 12 million years ago), when the atmospheric CO_2 concentration was naturally similar to or higher than it is today. Coupled with decades of previous study, these exciting results depict an unfamiliar world characterized by a warm deep ocean, and yet a large ice sheet was present on Antarctica. Both models and data agree that the Antarctic ice sheet in the Miocene was highly responsive to changes in the atmospheric CO_2 concentration, a clear cause of concern in the context of ongoing anthropogenic climate change.

1. Introduction

The middle Miocene (~17–12 Ma) is one of the key study intervals of the Cenozoic with respect to understanding past warm climate states. The Miocene climatic optimum (MCO, ~16.5–15 Ma) is the most recent interval with atmospheric CO_2 substantially elevated above that of the early 21st century, with boron isotope and alkenone $\delta^{13}C$-derived estimates (Sosdian et al., 2018; Super et al., 2018) constraining peak CO_2 to around 400–800 ppm, declining to 200–400 ppm after the Miocene climate transition (MCT, ~14.5–13 Ma). The atmospheric CO_2 concentration of the MCO gave rise to a profoundly different world to today, with global mean surface temperature ~3–6°C higher than preindustrial times (Hansen et al., 2013; Tierney et al., 2020) and a substantially reduced latitudinal temperature gradient (Goldner et al., 2014); also see the review paper in this issue for a more comprehensive summary of the climate and biota of the Miocene (Steinthorsdottir et al., 2020).

As is the case for most target study intervals in the Cenozoic, the oxygen isotopic composition ($\delta^{18}O$) of deep-ocean benthic foraminifera forms the starting point and the backbone of much of our understanding of these past worlds (Westerhold et al., 2020). Benthic $\delta^{18}O$ data record some combination of sea surface temperature (SST) in the regions of deep-water formation and global ice volume, the latter of which shifts the bulk composition of the ocean to positive values via the growth of ice sheets with a very negative isotopic composition. Building on earlier studies, a high resolution record from the equatorial Pacific (Holbourn et al., 2014) demonstrates a strongly orbitally paced climate, with peak warmth at ~15.6 Ma transitioning to peak mid Miocene glacial conditions in at least three major steps between 14.7 and ~13.8 Ma. The magnitude of the orbitally paced $\delta^{18}O$ oscillations throughout the mid-Miocene was ~ 0.5–0.75‰, lower than that of the upper Pleistocene (~1.5‰), but generally greater than the mid Pliocene (Lisiecki & Raymo, 2005). As such, benthic foraminifera $\delta^{18}O$ data (e.g. Miller et al., 2020), combined with sediment records from the ANDRILL core (Western Ross Sea), reveal a highly dynamic mid Miocene Antarctic ice sheet (Levy et al., 2016).

An enormous amount of progress has been made since the key features of climatic variation within the mid Miocene were first described (Douglas & Savin, 1975; Savin, 1977; Shackleton & Kennett, 1975; Vincent & Berger, 1985; Woodruff & Savin, 1991), although key questions remain. Foremost amongst these are, for example, the precise size of the Antarctic ice sheet and how very large ice volumes can be reconciled with intervals of overall relative warmth (see e.g. Stap et al., 2016). Lear et al. (2015) suggested that Antarctic ice volume following the MCT was likely greater than present, based on a multiproxy approach applied to benthic foraminifera. This study used methodology pioneered in earlier work (Lear et al., 2000; Rosenthal et al., 1997) to measure $\delta^{18}O$ and an independent paleothermometer (the ratio of Mg to Ca) in the same samples, in order to determine both the temperature of the deep ocean and the oxygen isotopic composition of seawater, the latter of which can be broadly related to continental ice volume. However, substantial uncertainty remained, not least because the Mg/Ca proxy is complicated by nonthermal influences such as secular changes in the Mg/Ca ratio of seawater (Evans & Müller, 2012; Horita et al., 2002) and the carbonate chemistry of the deep ocean (Lear et al., 2010).

Complex problems require new approaches such as those employed by a paper published as part of this special issue (Modestou et al., 2020). Here, I explain the importance of their data and place them into the broader context of proxy development and mid Miocene climate records, as well as providing an outlook for paleoclimate research in view of the many tools now at our disposal.

2. New Approaches, Renewed Confidence

Modestou et al. (2020) present deep sea temperature reconstructions based on the geochemistry of benthic foraminifera, but with a key difference. Rather than 'traditional' isotopic or trace metal analysis, the authors measured the clumped isotopic composition of the foraminifera shells. The basis of the proxy lies in the temperature-dependent relative abundance of heavy isotope pairs in the carbonate component of $CaCO_3$, in this case ^{13}C bonded to ^{18}O (e.g. Affek, 2012). The key advantage of this technique compared to previous paleothermometers is that knowledge of the isotopic or elemental composition of the seawater in which the foraminifera grew is not required, and no resolvable sensitivity to other hydrographic parameters has been found over the range that these are likely to have varied within the Phanerozoic (Tripati et al., 2015), that is, uncertainty is dominated by analytical reproducibility unlike all other paleothermometers (Figure 1). This circumvents the issue of separating temperature versus ice volume change inherent to the interpretation of traditional $\delta^{18}O$ data, or the complications associated with evolving seawater chemistry and the carbonate chemistry of the deep ocean which must be taken into account when interpreting Mg/Ca or Mg/Li measurements (Evans & Müller, 2012; Lear et al., 2010, 2015).

However, everything comes at a price. The reason that clumped isotope thermometry is applied to Miocene benthic foraminifera for the first time by Modestou et al. (2020), is that molecules containing more than one heavy isotope are extremely rare, and therefore very difficult to measure with the required precision. The first studies to report clumped isotope measurements of carbonate samples required ~15 mg of material (Ghosh et al., 2006), equivalent to >200 relatively large benthic foraminifera, which is at best challenging, and often impractical in terms of abundances in deep sea sediment cores. Later methodological advances (Meckler et al., 2014; Schmid & Bernasconi, 2010) reduced this sample size requirement by a factor of 10, opening up new possibilities in terms of carbonate archives. Modestou et al. (2020) apply this technique to samples recovered from ODP Site 761 (NW Australian margin, modern water depth 2,179 m, middle Miocene paleo water depth similar to modern (Holbourn et al., 2004)) spanning ~16.5–12 Ma, which includes

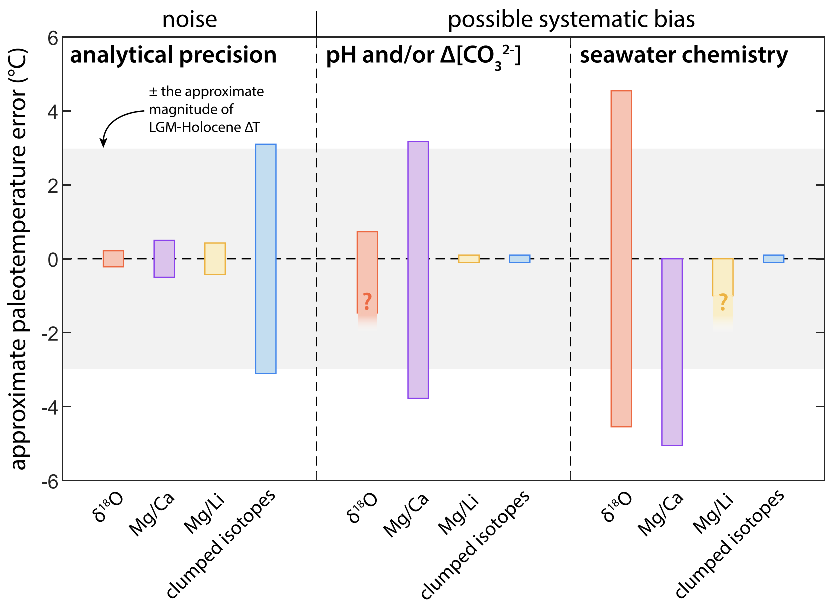

Figure 1. The approximate magnitude of the various sources of uncertainty affecting some common deep ocean temperature proxies based on the geochemistry of benthic foraminifera. Note that this assumes the worst-case scenario that no constraints on these nonthermal controls exist, which is often not the case. In addition, relative temperature reconstructions can be much more precise than this figure implies (e.g., relative changes cannot be biased if the study interval is shorter than that over which seawater chemistry can change, although the absolute temperature reconstructions may be biased if seawater chemistry was different to modern). The magnitude of the bars relating to seawater chemistry reflect both the degree and the direction which these parameters have varied in the Neogene only. The figure is intended as an approximate guide; these values may be species/site specific. A pH (CO_3^{2-}) effect on foraminifera $\delta^{18}O$ has been suggested (Zeebe, 1999) but not (yet) found in benthic species (Marchitto et al., 2014). The effect of seawater chemistry on the Mg/Li proxy is not constrained (little is known about the possible secular evolution of seawater [Li]).

much of the MCO as well as the MCT. The data show that the deep ocean cooled by ~3°C between the MCO and after the MCT, within uncertainty, although substantially greater than a previous estimate based on Mg/Ca (Lear et al., 2015). While this is in-line with the ~200–400 ppm decrease in atmospheric CO_2 across the MCT (Sosdian et al., 2018; Super et al., 2018), more surprising are the absolute temperature reconstructions; the temperature at this site during the MCO was 11.0± 1.7°C, decreasing to 8.1± 1.8°C after the MCT. This is 5°–8°C warmer than the water currently bathing this site, a very large change; for context, the magnitude of the temperature change in the deep ocean between the last glacial maximum (LGM) and the Holocene was ~3°C (Adkins et al., 2002). Encouragingly, the absolute clumped isotope temperatures are in excellent agreement with those derived from Mg/Ca data from the same site, especially when changes in bottom water carbonate chemistry are accounted for using Li/Ca (Lear et al., 2010). This adds confidence to the results overall, and more broadly to benthic Mg/Ca and Mg/Li derived temperatures throughout the Cenozoic.

Remarkable findings require careful consideration of alternative explanations. Key to the integrity of benthic clumped isotope data is that no resolvable species or group-specific calibration differences have been found (Meinicke et al., 2020). Moreover, diagenetic alteration can substantially bias both $\delta^{18}O$ and Mg/Ca-derived reconstructions (Kozdon et al., 2013), but benthic clumped isotope data have been shown to be minimally sensitive to diagenetic recrystallization (Leutert et al., 2019) likely because this process – if present – takes place at a temperature similar to that during the life of the foraminifera (Evans et al., 2018); clumped isotope thermometry, unlike $\delta^{18}O$, is sensitive to temperature but insensitive to the bulk isotopic composition of the sample. For these reasons, the temperature reconstructions of Modestou et al. (2020) appear robust, and do not suffer from the nonthermal influences that complicate the interpretation of traditional stable isotope and trace element proxies in terms of absolute temperature (Figure 1). Indeed, these deep ocean temperature data are supported by mid/high-latitude sea surface temperature (SST) estimates (Levy et al., 2016; Shevenell et al., 2004; Super et al., 2018), which adds support to the notion of a greatly

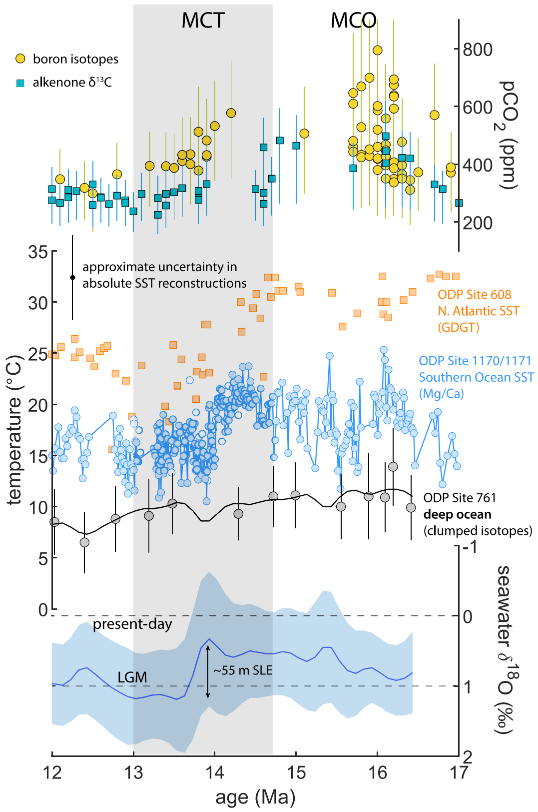

Figure 2. Middle Miocene reconstructions of atmospheric CO_2 (Super et al., 2018; Sosdian et al., 2018), mid latitude sea surface temperature (SST) from Mg/Ca (Shevenell et al. (2004) reinterpreted following Gray & Evans (2019)) and GDGTs (glycerol dialkyl glycerol tetraether lipids; Super et al., 2018), deep ocean temperature from clumped isotopes (Modestou et al., 2020), and seawater $\delta^{18}O$ from coupled clumped isotope- $\delta^{18}O$ measurements of benthic foraminifera. SLE denotes sea level equivalent, using the Miocene $\delta^{18}O$-sea level relationship of Langebroek et al. (2010).

reduced latitudinal SST gradient and therefore much warmer temperatures in the regions of deep water formation (Figure 2).

3. Deep Heat but Big Ice?

The clumped isotope data come from just one site, and modeling indicates substantial heterogeneity in the thermal response of the deep ocean as a result of changes in deep water formation driven by ice growth on Antarctica (Knorr & Lohmann, 2014). Of specific relevance to the results of Modestou et al. (2020), deep water masses in the eastern Indian ocean are predominantly related to Antarctic Intermediate Water (AAIW) and Antarctic Bottom Water (AABW)/Circumpolar Deep Water (CDW), with ODP Site 761 (~2,200 m paleo water depth) currently sitting close to the depth of the boundary between AAIW and deeper water masses (Holbourn et al., 2004; Warren, 1981; Woo & Pattiaratchi, 2008). This raises the possibility that data from ODP Site 761 potentially relate to water masses that are a few degrees warmer than those bathing much of the deep ocean. However, benthic $\delta^{18}O$ at ODP Site 761 closely tracks that recorded at many other sites in other basins (e.g. Flower & Kennett, 1995; Holbourn et al., 2014) and is in close agreement with data from ODP Site 1,237 (SE Pacific; Holbourn et al., 2005) which is currently situated at 3,212 m water depth and bathed by Pacific Central Water. In addition, benthic $\delta^{18}O$ values from ODP Site 761 are in good agreement with the long term smooth through the most recent Cenozoic compilation (Westerhold et al., 2020), indicating that this site is not substantially offset from the global mean. Therefore, heterogeneity in deep ocean temperature and/or $\delta^{18}O_{sw}$ does not appear to be a complication for the interpretation of middle Miocene data from ODP Site 761. More broadly however, analysis of a multisite compilation by Cramer et al. (2009) highlighted that benthic foraminifera $\delta^{18}O$ may differ by up to ~0.8% between sites, equivalent to ~3°C– this is an issue that needs careful consideration when working with a data set derived from a single site.

If the clumped isotope results are indeed globally representative as suggested by the comparisons given above, the data can be coupled to traditional $\delta^{18}O$ analyses to constrain the oxygen isotopic composition of seawater through the middle Miocene, which is what Modestou et al. (2020) go on to do. This technique has been applied many times before (e.g. Elderfield et al., 2012; Lear et al., 2000), albeit with the Mg/Ca paleothermometer as the independent temperature constraint, which is influenced by several nonthermal factors (Figure 1). The new results are surprising; taken at face value, the combined clumped isotope-$\delta^{18}O$ data show that $\delta^{18}O_{sw}$ was more positive than today throughout the middle Miocene (Figure 2). Given a lack of evidence for northern hemisphere glaciation at this time, this requires an Antarctic ice sheet larger than at present, or an alternative explanation for an isotopically heavy deep ocean. One possibility is the formation of ice with an isotopic composition much lighter than at present, which could result from a topographically higher ice sheet, or a greater average distance between Antarctica and the source of precipitation. While factors such as these might be important in understanding the fine detail of the record (Langebroek et al., 2010), the magnitude of the signal is such that this clearly cannot be the principal explanation – it would require Antarctic ice with an infeasibly light isotopic composition.

Given that an isotopically heavy seawater $\delta^{18}O$ during the mid-Miocene now appears well constrained, the question is: how can atmospheric CO_2 substantially higher than preindustrial and a very warm deep ocean be reconciled with an Antarctic ice sheet larger than today? Earlier work suggested that evaporation-driven deep water formation via the southwards movement of highly saline water from the Tethys and Indian Ocean toward Antarctica could provide the mechanism of subduction of warm, salty surface waters (Woodruff & Savin, 1989). If correct, this would point to an unusual mode of Miocene deep water formation, rather than a state-dependent relationship between surface temperature and ice volume. However, the interpretation of Woodruff and Savin (1989) has been questioned (Smart et al., 2007), while the near closure of the connection between the Tethys and Indian Ocean broadly coincident with the MCT precludes this being the only explanation because Modestou et al. (2020) reconstruct positive $\delta^{18}O_{sw}$ throughout the middle Miocene. Indeed, modeling work (Hamon et al., 2013) argues for a role of the closure of the Tethyan gateway in driving further expansion of the Antarctic ice sheet after 14 Ma, rather than providing an alternative explanation for the isotopic composition of the deep ocean.

If ocean circulation changes alone cannot solve the conundrum, the question is finally whether there is observational evidence for a large mid-Miocene Antarctic ice sheet, and if so, whether this can be reproduced by ice sheet models. Both seismic data and sedimentological evidence demonstrate that a grounded marine ice sheet was at least periodically present in the western Ross Sea, supporting the notion of a relatively large mid Miocene ice sheet (Chow & Bart, 2003; Levy et al., 2016). Moreover, by coupling a general circulation model to a regional ice sheet model, Gasson et al. (2016) were able to reconstruct the magnitude of $\delta^{18}O_{sw}$ change between the MCO and post-MCT conditions (modeled $\Delta\delta^{18}O_{sw} = 0.53\%$; Modestou et al., 2020 derive 0.6%). Importantly, this modeling effort demonstrates that the size of the ice sheet at a given atmospheric CO_2 is sensitive to Antarctic topography, as has been previously identified for other time intervals such as the Eocene Oligocene transition (Wilson et al., 2013). Specifically, Gasson et al. (2016) reconstruct an ice volume applicable to the cooler intervals of the mid Miocene that is ~35% larger than at present, driven in part by the overall higher bedrock topography and greater extent of land above sea level (marine-grounded ice sheets are more responsive to temperature change, see e.g. Pollard & Deconto, 2016). In turn, this larger than modern and isotopically lighter ice sheet would result in a positive deep ocean $\delta^{18}O_{sw}$, in line with Modestou et al. (2020). Much remains to be understood, however. It is important to note that Antarctic ice volume throughout the middle Miocene may have been much more variable than implied by the relatively low-resolution data of Modestou et al. (2020). For example, it has been suggested that peak middle Miocene warmth was potentially associated with little ice on Antarctica (Miller et al., 2020; Stap et al., 2016; discussed in more detail in Steinthorsdottir et al., 2020). In addition, the Antarctic ice sheet response to pCO_2 depends strongly on multiple factors such as the dynamics of pCO_2 change, orbital parameters, and precipitation lapse rate (Stap et al., 2019). Higher resolution proxy CO_2 and temperature datasets will help to resolve which of these factors were most important in controlling the magnitude of ice volume changes across the MCT.

Beyond the Miocene, the finding of a very warm deep ocean during the MCT has important implications to the broader field of paleoclimatology. For example, it could imply that the relationship between global mean surface temperature (GMST) and the temperature of the deep ocean is more complicated than implied by some methods that have been used to derive GMST of past warm intervals (see Hansen et al., 2013; Inglis et al., 2020). Indeed, similarly complex relationships between ice volume, deep ocean temperature, and pCO_2 have been found for other intervals (O'Brien et al., 2020). Together, these data argue for more nuanced approaches to deriving pre-Pliocene GMST from deep ocean proxy data.

4. Outlook

Enormous progress has been made since the climatic changes of the middle Miocene were first identified using benthic foraminifera geochemistry (Douglas & Savin, 1975; Shackleton & Kennett, 1975; Vincent & Berger, 1985; Woodruff et al., 1981). Nonetheless, further work is required, and our understanding of Miocene climate and the relationship between the spatial pattern of surface temperature, pCO_2, and Antarctic ice volume is far from complete. Foremost amongst the outstanding questions is how the overall very positive $\delta^{18}O_{sw}$ values throughout the interval can be explained. Even at the maximum extent of the 95% confidence intervals, the new data from Modestou et al. (2020) would require an ice sheet similar in size to modern throughout the peak warmth of the MCO (400–800 ppm CO_2), whereas a recent ice sheet model suggest a greatly reduced Miocene ice volume at 2 × preindustrial CO_2 (Gasson et al., 2016). Future work specific to this aspect of Miocene climate should therefore focus on: understanding whether such large ice volumes can be reconciled with pCO_2 higher than present-day, understanding whether any unidentified bias exists in the benthic foraminifera $\delta^{18}O$ record, producing more high-latitude SST data, and of course, a renewed model and model-data intercomparison effort (the latter will be tackled by the forthcoming Miocene model intercomparison project, MioMIP; Burls et al. (2021)). Taking a longer view, the benthic clumped isotope data presented by Modestou et al. (2020) are a first step toward producing a clumped isotope version of the Cenozoic benthic $\delta^{18}O$ stack – a mainstay in paleoclimatology which has been successively refined over the last two decades (Cramer et al., 2009; Westerhold et al., 2020; Zachos et al., 2001, 2008). Unraveling the full history of deep ocean temperature and ice volume over the last 65 Myr using this new approach will be a major achievement.

Despite the challenges that remain, new methodologies such as that utilized by Modestou et al. (2020) as well as an improved understanding of existing techniques mean that the confidence with which we interpret proxy data is changing. The paleoclimate literature is scattered with paradoxes, famous examples of which are the Eocene cool tropics paradox (see e.g. Barron, 1987; Pearson et al., 2001) and the related equable climate paradox (Huber & Caballero, 2011; Wing, 1994). The reasons for terming these phenomena as paradoxes are varied, but – in my view – derive in large part from our understanding of the proxies. That is not to imply that little is left to be understood about the climate system, rather that we, as a community, now have a proxy toolbox increasingly routed in a firm mechanistic understanding, while multiproxy approaches enable multiple aspects of the system of interest to be simultaneously constrained. Coupled with advances in climate and ice sheet modeling, and community model-data comparison projects (e.g. Hollis et al., 2019), I anticipate that the questions we ask will increasingly shift away from whether a past climate state was characterized by a given feature, toward how such features can be explained; the paradoxes will become increasingly rare. There has never been a more exciting or more important time to perform paleoclimate research.

Data Availability Statement

No new datasets are presented here. The derivation of Figure 1 is described in Text S1 and S2. The data shown in Figure 2 are available from Super et al. (2018), Sosdian et al. (2018), Shevenell et al. (2004), and Modestou et al. (2020).

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